

RADIO EMISSION FROM MAGNETARS

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ABSTRACT

We discuss properties of the expected radio emission from Soft Gamma-ray Repeaters (SGRs) during their bursting activity in the framework of the model of Thompson, Lyutikov and Kulkarni (2002), in which the high energy emission is powered by the dissipation of super-strong magnetic fields in the magnetospheres through reconnection-type events. Drawing on analogies with Solar flares we predict that coherent radio emission resembling solar type-III radio bursts may be emitted in SGRs during X-ray bursts. The radio emission should have correlated pulse profiles with X-rays, narrow-band-type radio spectrum with $\Delta\nu \leq \nu$ with the typical frequency $\nu \geq 1$ GHz, and, possibly, a drifting central frequency. We encourage sensitive radio observations of SGRs during the bursting activity.

1. INTRODUCTION

Soft Gamma-ray Repeaters (SGRs) and Anomalous X-ray pulsars (AXPs) have been identified as isolated magnetized neutron stars – magnetars (for recent reviews see, e.g., Thompson 2001). Both SGRs and AXPs have spin periods in the range $P = 6 - 12$ s, characteristic ages $P/2\dot{P} = 3 \times 10^3 - 4 \times 10^5$ yr, and X-ray luminosities $L_X = 3 \times 10^{34} - 10^{36}$ erg s $^{-1}$. SGRs are characterized primarily by occasional repeating bursts of soft gamma rays, as well as by rare giant gamma ray outbursts that are at least two orders of magnitude higher in fluence than the smaller events (two have been detected so far). The more common small amplitude bursts have durations of less than ~ 1 s, have rise times of typically a few tens of msec, and have fluences that are roughly correlated with duration (Gögüs et al. 2001). In quiescence, SGRs display X-ray pulsations with periods in the range 5-8 s, spin-down rates in the range $10^{-11} - 10^{-12}$, and X-ray emission, most prominent below ~ 10 keV, that is well-described by a power law with photon index ~ 2 .

Recently Gavril et al. (2002) have reported an observation of bursts from AXP. If confirmed, this would establish a close relation between the AXPs and SGRs; similarity between the burst properties of both classes argue in favour of the same mechanism of the X-ray burst production. Below we concentrate on a better studied case of SGR bursts, but most of the arguments given may be applied to AXP bursts as well.

The radio counterpart status of SGRs has been controversial. Shitov (2000) reported the detection of pulsed emission from SGR 1900+14 at 111 MHz with the Pushchino Radio Observatory. However, using Arecibo in 1998, Lorimer & Xilouris (2000) observed SGR 1900+14 yet detected no such radio pulsations. Indeed, no radio pulsations have been detected from any of the SGRs. This is somewhat surprising since recent radio surveys have discovered pulsars with polar magnetic fields approaching 10^{14} G (Camilo et al. 2000), continuous with the lower range of fields deduced from AXP spin-down.

Recently Thompson, Lyutikov and Kulkarni (2002) have proposed a model of the SGRs based on the dissipation of

the internal super-strong magnetic field, generated by a hydromagnetic dynamo as the star is born, by external currents flowing in the magnetosphere. They argued that the currents supporting the strongly twisted field inside the neutron stars are gradually transported into the external magnetosphere, where they can be efficiently dissipated. The rate with which the currents are transported into the magnetosphere depends on the tensile strength of the neutron star crust and the strength of the non-potential (current-carrying) magnetic fields. Two regimes are possible: for plastic-type deformations of the crust the twist is implanted at a more or less constant rate, while for fracturing-type deformations the twist is implanted in sudden events. Overall, the behavior of the magnetic field resembles that of the Sun, as the current is transported from the matter-dominated star into the magnetically dominated corona. The parallels between the dynamics of the solar and magnetar field loops extends even further: in both cases the footpoints are believed to be moved by the torques acted upon them by the twisted magnetic fields (in addition, on the Sun, some footpoints are moved around by the convective motions).

With reservation for our understanding of reconnection and particle acceleration, we propose here that the bursting activity of AXPs and SGRs is due to the reconnection-type events in which magnetic energy stored in the non-potential magnetic field is released in the magnetosphere. Pushing the analogies with the Sun even further, we argue that both the persistent emission and the flares, including giant flares, may result from discreet energy releasing events, in which the external field relaxes to a lower energy state with a different field line topology. This requires that the external magnetic shear build up gradually, and that the outer crust of the neutron star is deformed plastically by internal magnetic stresses. The energy stored in the external twist then does not need to be limited by the tensile strength of the crust, but instead by the total external magnetic field energy.

Any suggestion of the importance of reconnection in astrophysical sources may only be based on the empirical relations obtained from Solar observations. The Solar magnetosphere structure and temporal behavior is extremely

complicated, as is beautifully illustrated by the latest images from the SOHO and TRACE satellites^{1 2}. It seems almost impossible to predict the behavior of the magnetosphere. Yet, there seem to be fairly general scaling laws, which extend from the smallest scales of the solar flares to magnetically active stars (e.g. T Tauri), that relate, for example, the magnetospheric activity as observed through high energy emission to the total magnetic flux and radio emission.

The two such correlations that we will rely on are (i) the linear dependence of the X-ray luminosity on the magnetic flux (e.g., Johns-Krull et al. 2000), which shows over 10 decades in X-ray and magnetic fluxes; and (ii) a strong correlation between the radio activity and the high energy activity, also extending from solar flares to stars. On the Sun the radio intensity of large solar flares, when observed, is linearly proportional to the X-ray flux (Sakurai 1974). Magnetospheric behavior 100 times more active both in terms of largest flares and flare frequency has been observed.

The direct consequence of the reconnection is the generation of radio emission, which always accompanies solar X-ray flares. The natural prediction is then that the radio emission should be observed from SGRs during bursts. Below we concentrate on SGRs, keeping in mind that burst may have already been observed from AXPs (Gavril et al. 2002). Here we discuss the expected properties of the radio emission of the SGRs, offer the best strategy for their detection and discuss possible effects that may prevent the detection of radio emission from SGRs.

2. SOLAR FLARES

Energy dissipation in solar flares is a generically non-linear phenomena: explosive-type instabilities initially grow exponentially (and thus are often called “avalanches”) and saturate after a few e-folding growth times, after all locally available free energy has been exhausted (Priest and Forbes 2002). The mechanism responsible for impulsive reorganization is not established, yet it seems that the dissipation takes place in spatially separated, unresolved complex structures, including small scale structures. X-ray and optical observations of the Sun show fine scale strands down to the instrument resolution (~ 30 km – micro and nano-flares), implying that the elementary heating processes are still unresolved. Thus, the Solar corona is active on all scales, from the solar radius, to granular convection and subarcsecond flux tubes. It is still not clear whether the continual dissipation of the small-scale current sheets dominates the heating of the closed field line regions of the corona, or whether the dissipation is dominated by the large scale current sheets, which involve a global rearrangement of the corona.

Statistical studies of solar energy release events, e.g. the distribution of event number versus energy content as observed at hard X-rays, have led to a description in terms of avalanches in a corona which has stored energy and is in a state of self-organized criticality (Lu & Hamilton 1991).³ The power-law distribution $N(E) \sim E^\alpha$ naturally follows from such a model since the system under consideration

has no characteristic spatial scale above the elementary scale of the smallest avalanche (the smallest energy release event), up to the system size, the size of active regions.

3. PERSISTENT AND BURST EMISSION FROM RECONNECTION

A number of facts points to the magnetospheric origin of SGR burst (and possibly persistent) emission. The short rise time of SGR bursts may be explained in the magnetar model only if originating in the magnetosphere. In case of persistent emission, the initial energy release may also happen in the magnetosphere due to unresolved small scale events. Later, the energetic particles will heat the crust that would produce the thermal emission.

The studies of the statistics of the SGR bursts from SGR 1900+14 (Gögüs et al. 1999) have found a dependence similar to that of solar flares of the number of bursts on their fluences with a power-law index 1.66 over 4 orders of magnitude. The distribution of time intervals between successive bursts from SGR 1900+14 is also consistent with a log-normal distribution.

Another type of correlation expected in the reconnection model is the correlation between the burst duration and total release energy. This is a natural correlation since larger bursts are required to tap into larger volumes of the energy reservoir. Such a correlation indeed was seen in the SGR bursts by Gögüs et al. (1999) who concluded that “in all [...] statistical properties, SGR bursts resemble earthquakes and solar flares more closely than they resemble any known accretion-powered or nuclear-powered phenomena”.

Other circumstantial evidence favoring magnetospheric emission includes (i) SGR bursts come at random phases in the pulse profile Palmer (2000) - this is naturally explained if (even only one!) emission site is located high in the magnetosphere, so that we see all the bursts (if the bursts were associated with a particular active region on the surface of the neutron star, one would expect a correlation with a phase); (ii) pulsed fraction increases in the tails of the strong bursts, keeping the pulse profile similar to the persistent emission (Woods 2002) - this is easier explained if the energy release processes occurring high in the magnetosphere after the giant burst are connected to the same hot spot on the surface of the NS as the field which are active during the quiescent phase. (iii) weak black-body component in the tail of the strong bursts is more consistent with the magnetospheric emission. (iv) smaller fluence SGR events, have harder spectra than the more intense ones (Gögüs 2002) (this is also true for the spikes of multi-structured bursts); this is consistent with short events being due to reconnection, while longer events have a large contribution from the surface, heated by the precipitating particles.

4. RADIO EMISSION FROM FLARES

Solar flares release magnetic energy in three equally important channels: thermal heat, bulk motion of plasma and energetic supra-thermal (and/or accelerated) particles. Solar flares are often accompanied by radio bursts,

¹ <http://sohowww.nascom.nasa.gov/>

² <http://vestige.lmsal.com/TRACE/>

³ Alternative interpretations include the early model of Rosner & Vaiana (1978) and Aschwanden et al. 1998

most often by what is called Type-III bursts (Bastian et al. 1998). Type-III radio bursts are signatures of energetic electrons generated during solar flares, traveling along the magnetic coronal field lines⁴. As a result, electrostatic plasma turbulence develops. Electromagnetic radio emission is generated in the collision of two plasma waves. The resulting emission is a narrow-band emission above the second plasma harmonic $\omega \sim 2\omega_p$. We propose that similar coherent emission may be generated in SGRs. Since the radio emission is generated by the electrons accelerated at the reconnection site, we predict that if the radio emission is detected during the bursting phases of SGRs, its intensity and profile will be strongly correlated with the X-ray bursts.

Generally, two types of particles acceleration have been proposed in the context of solar flares: (a) acceleration by parallel electric fields and (b) stochastic drift acceleration by perpendicular electric fields. DC acceleration is expected to work as well in SGRs, while the stochastic one is likely to be suppressed by the super-strong magnetic fields. We do not expect that Type-II bursts, which arise due to the shock acceleration in the solar magnetosphere will be produced in the SGRs, since the plasma density there is extremely small, so that except in the reconnection region, the magnetosphere is well-described by the force-free approximation, which does not allow the existence of shocks.

5. EXPECTED PROPERTIES OF SGR RADIO FLARES

5.1. Temporal behavior

Energy release in reconnection appears to be a non-stationary transient phenomenon resulting, presumably, from the spatially fragmented structure. The temporal behavior of Solar flares has several time-scales, associated with different spatial scales of the reconnecting structures. Similarly, the radio emission is expected to be non-stationary and multi-times scaled, keeping the memory of the energy release history.

In reconnection, the shortest time scale is related to the Alfvén crossing time of the magnetic structures of length L : $\tau_r \sim L/v_A$ (for the Sun this is ~ 1 sec). The scale L corresponds to the length of the reconnecting arc, which for the SGRs may be as small as a fracturing of radius and as large as the light cylinder radius. For flares occurring close to the surface we may assume $L \sim R_{NS}$. The Alfvén velocity v_A equals the speed of light in the force-free magnetosphere. The observed rise time of the SGR X-ray flares, ≤ 10 msec, is consistent with being related to the Alfvén time scale. For the observed bursts the rise time is limited by the intensity of the burst - weaker bursts are expected to have shorter rise times (Gögüs 2002). The shortest rise time is expected to be of the order of light travel time across the neutron star - tens of microseconds. This time scale also gives the duration of shortest spikes in the burst structure. Radio bursts should have similar rise times, with a possible time-delay to allow for the plasma instabilities to develop after the main X-ray burst. The

overall duration of the burst depends on global structure of the reconnection region - the reconnection at one point may trigger reconnection at other points.

Radio emission should be more intermittent than the X-ray emission, reflecting the fact the its intensity depends both on the production rate, monitored well by the X-ray flux, and often subtle conditions for the development of kinetic instabilities (e.g. the requirement of beam velocity to be larger than the thermal velocity of the plasma particles).

5.2. Spectra

Thompson et al. (2002) discussed the properties of the strongly twisted magnetosphere of the SGRs. Qualitatively, the maximum current that the magnetosphere can support corresponds to the toroidal field reaching in strength approximately a poloidal field $B_\phi \leq B_p$. Below we assume that such strong currents are indeed flowing in the SGR magnetosphere (the strength of the current may be inferred from the persistent luminosity of SGRs, see Thompson et al. 2002, eq. (34)). The velocity of the charge carriers is weakly relativistic, $v \simeq c$. From the induction equation we then find the current

$$j \sim env \sim cB/(4\pi R) \quad (1)$$

and the plasma density n and the plasma frequency $\omega_p = \sqrt{4\pi e^2 n/m}$:

$$n \sim B/(4\pi eR), \omega_p^2 \sim \omega_B c/R \quad (2)$$

Numerically, for $B_{NS} = 10^{14}$ G, $\omega_B = \omega_{B_{NS}} \tilde{r}^{-3}$, where $\tilde{r} = R/R_{NS}$, $\omega_{B_{NS}} = 2 \times 10^{21}$ rad/sec,

$$\omega_p = \frac{\sqrt{\omega_{B_{NS}} c/R_{NS}}}{\tilde{r}^2} = 7 \times 10^{10} (\tilde{r}/10)^{-2} \text{rad/sec} \quad (3)$$

The self-similar model of Thompson et al. (2002) predicts that most of the non-potential energy of the magnetosphere is concentrated near the stellar surface, at $R \leq 10R_{NS}$. Eq. (3) may explain why the radio emission from SGRs has not been detected yet and suggests the strategy for further searches. If the coherent radio emission is generated near the stellar surface and is associated with the local plasma frequency ω_p , then,⁵ from eq. (3), we may expect that the coherent radio emission should be generated at high frequencies, $\nu \gtrsim 1\text{GHz}$; below that the plasma frequency is above the observed frequency, so that plasma waves cannot propagate.

The radio emission of SGRs is expected to be qualitatively different from the normal radio pulsar emission. In conventional radio pulsars the presence of the primary beam with super-relativistic Lorentz factors is imperative for the generation of radio emission. In SGRs this primary beam may not be created since the Goldreich-Julian density is much smaller than the density of the currents required to support the twisted magnetic field. If a large charge density is indeed generated on the open field lines,

⁴Particle acceleration is, in fact, not necessary for the Type-III bursts. It may be generated either by the thermal component of the plasma heated by the reconnection - as the faster particles leave the reconnection region conditions for the bump-in-tail instability develop not far from the reconnection region) or by the fast supra-thermal particles accelerated by the DC electric fields in the reconnection region.

⁵Generation of coherent emission at the plasma frequency near the stellar surface is, in fact, *not* how we believe the pulsar radio emission is produced, see below.

the particle accelerator, operating in the rotationally powered pulsars, may be swamped and no pulsar-type radio emission is generated. This may be another reason why radio emission has not yet been detected from SGRs.

The radio emission of SGRs during bursting activity will resemble the solar radio Type-III bursts. In solar Type-III bursts the energy is consecutively converted from the magnetic energy into fast particles, then into electrostatic plasma waves and finally into escaping electromagnetic waves. The frequency of the generated EM waves is the double of the plasma frequency $\omega \sim 2\omega_p$. Thus, one expects a *narrow-band emission* $\Delta\omega/\omega \leq 1$. The growth rate of Langmuir instability

$$\Gamma \sim (n_b/n)^{1/3} \omega_p \leq \omega_p \quad (4)$$

(n_b is the beam density) is indeed much higher than the dynamical time

$$\Gamma/(c/R) \sim \sqrt{\omega_B/(c/R)} \gg 1 \quad (5)$$

Thus, the plasma instability has enough time to develop.

A distinct feature of the type-III burst is the drift of the central frequency due to the spatial propagation of the emitting beam in the inhomogeneous plasma. Since the velocities of the emitting electrons are likely to be weakly relativistic, the resulting emission may not be narrow-band, as the electrons propagate in the inhomogeneous plasma. Still, one may expect the frequency drift of the peak of radio emission, characteristic of Type-III bursts. Since the plasma density in the SGR magnetosphere is $\omega_p \sim \tilde{r}^2$, then if fast electrons propagate with $v \sim c$, then the central frequency will move as $\omega_{max} \sim t^{\pm 2}$ taking into account the possibility of upward and downward movement. The multi-polar structure of the magnetosphere may change this simple dependence.

It may also be possible to observe the U-type subclass of the Type-III bursts: in this subclass the central frequency first decreases and then starts to increase as emitting electrons move along the closed field lines, reach the maximum height above the stellar surface (at this point the density is minimal, so is the frequency of emission) and then return to the stellar surface.

5.3. Expected Flux

The radio brightness of SGR bursts may be estimated using the energy partitioning in the solar flares, where the energy release in radio is typically 10^{-4} of the energy released in hard X-rays⁶ (plus an approximately similar amount of energy is released in bulk motion, thermal heating and Cosmic rays). Since the X-ray luminosity of flares is $\sim 10^{36} - 10^{39}$ erg/sec, the expected radio luminosity $\sim 10^{33} - 10^{35}$ erg/sec, which at a distance ~ 10 kpc and the observing frequency $\sim 1\text{GHz}$ will produce a flux of $\sim 1 - 1000\text{Jy}$, which may be easily detectable.

6. DISCUSSION

We encourage radio observations of SGRs and AXPs during their active phase at high frequencies $\geq 1\text{GHz}$. This requires catching a burst in simultaneous radio and X-ray observations.⁷ During its active phase SGR 1900+14 produces bursts every ~ 50 seconds, emitting $\sim 10^{38}$ ergs/sec burst every ~ 10 minutes (Gögüs 2002). The radio flux from such a burst ~ 10 Jy can be easily detected. Though larger flares are less likely ($dN/dE \sim E^{-1.66}$) a flare 10 times stronger is still observed once per hour. The search should be done in a pulsar mode with fast timing. Initial detection will naturally require a search in the DM space; the frequency drift of the emission may complicate the DM search. A strong correlation with the X-ray burst may provide an additional help in detecting radio bursts, especially after the first one is seen and time delay between the X-rays and radio due to the ISM propagation is measured.

Persistent radio emission from SGRs may also be observed, though the expected fluxes $\sim 1 - 10$ mJy (based on the same radio/X-ray luminosity ratio of 10^{-4} and the persistent X-ray emission from SGRs $\sim 10^{34} - 10^{35}$ ergs/sec) may be too faint.

A number of factors may preclude the detection of radio emission from SGR burst: (i) reconnection in SGRs may be qualitatively different from the reconnection on the Sun; (ii) radio emission may be strongly absorbed (or scattered at $r < r_a$) at the cyclotron resonance inside the SGR magnetosphere. Incidentally, if we assume that a ~ 6 sec pulsar strongly scatters or absorbed radio waves inside the light cylinder, then one would expect a sharp cut-off above ~ 100 MHz, consistent with the claims of detection of SGR 1900+14 frequencies and non-detection at higher frequencies (Shitov et al 2000, Gil et al. 1998); (iii) abundant pair production during the burst may significantly increase the plasma density and the plasma frequency, pushing the radio emission to higher frequencies.

Another possible mechanism of radio emission generation – due to the loss-cone instability and at the anomalous cyclotron-Cherenkov resonance – are not likely to operate in SGRs. In the super-strong magnetic fields of SGRs electrons lose their transverse energy almost immediately. Thus, we don't expect any adiabatically trapped electrons to exist near the neutron star radius (the adiabatic radius, where the cyclotron decay time becomes equal rational period is $r_a \sim 5 \times 10^3 R_{SN} \sim 0.15 R_{LC}$).⁸ So no loss-cone instability will develop. Since the difference of the refractive index of plasma from unity is negligible $n - 1 \sim c/R\omega_B \sim 10^{-18}$, no anomalous cyclotron - Cherenkov instability (Lyutikov et al. 1999) will develop either. We can also neglect the (frequency-independent) dispersion inside the magnetosphere.

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⁶The direct application of the radio efficiency of the Solar flares to magnetars is naturally only a guess.

⁷We would like to stress that we predict a coherent emission *during* the bursts, not the cyclotron emission from the plerionic nebular after the burst (Frail et al. 1999)

⁸Cyclotron transition time $\tau = c/(r_e \omega_B^2)$; it equals the rotational period at $r_a = (P\omega_{BSN}^2 r_e/c)^{1/6} R_{NS}$

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